PITCH-ANGLE DISTRIBUTION OF THE PHOTOELECTRONS AND ORIGIN OF THE GEOMAGNETIC ANOMALY IN THE F_2 LAYER

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Pitch-Angle Distribution of the Photoelectrons and Origin of the Geomagnetic Anomaly in the F_2 Layer

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A major anomaly of the F region is the 'equatorial' or 'geomagnetic' anomaly, which consists of the pronounced minimum of f_oF_2 on the geomagnetic equator and two maximums near 20° north and south geomagnetic latitude, at meridian hours and in the afternoon, in every season. A recent theoretical approach [*Goldberg and Schmerling*, 1963] favors the hypothesis that a diffusion process from the equator along the magnetic lines of force can produce the enhancement of f_oF_2 in both hemispheres. However, it has been suggested that this process alone is not sufficient to explain completely the observed anomaly [*Rishbeth et al.*, 1963].

It is the purpose of this letter to present in some detail one simple mechanism that also may play a role in the explanation of the anomaly. This mechanism is based on a detailed analysis of the physical processes that the photoelectrons undergo in the upper atmosphere.

It is generally assumed that the photoelectrons produced in the atmosphere by solar ultraviolet radiation undergo physical processes which contribute to the F-region electron distribution only at the altitudes where they are produced. In this hypothesis no importance is attached to the actual angular distribution of the photoelectrons produced by the photoelectric effect. This distribution [*Heitler*, 1944] is peaked at right angles with respect to the direction of the incident photons according to a $\sin^2 \theta$ law (θ is the angle between the photoelectron velocity vector and the incident photon direction). On the other hand, the incident photon beam, as a whole, is not polarized, so that the azimuthal photoelectron distribution is on the average practically uniform.

At rather low altitudes, in the E and F_1 layers, the thermalization lifetime of the produced photoelectrons is very short, owing to their small mean free path with respect to all the possible physical loss processes. However, this is not the case for the upper F_2 region, where we can assume [*Hanson*, 1963] that the most important energy loss of the photoelectrons occurs in elastic collisions with ambient electrons. An immediate consequence of the large mean free path is that the photoelectrons are subject to some motion after their production and that the actual distribution of the production rate can differ from the case of 'local' thermalization. The perturbation is related to latitude and to the time-variable effect of the geomagnetic field on the $\sin^2 \theta$ angular distribution of the ejected photoelectrons. We suggest that what is called 'anomaly' could just be, at least partly, the result of the redistribution of the photoelectrons produced locally owing to the presence of the geomagnetic field. Anyway, we must point out that the experimental datum we have is the density of the ambient thermal electrons, so that its comparison with the photoproduction rate remains to some extent arbitrary.

For a centered magnetic dipole with its axis aligned with the geographical axis, the corresponding pitch angle distribution is given by the function (Mariani, manuscript in preparation, 1963)

$$g(\alpha) = \tfrac{3}{4} \sin \alpha [\sin^2 \alpha + \sin^2 \beta (1 - \tfrac{3}{2} \sin^2 \alpha)]$$

The quantity $g(\alpha)d\alpha$ gives the fraction of electrons cm^{-3} sec^{-1} with pitch angle α between α and $\alpha + d\alpha$. The angle β is the angle between the direction of the incident photon and the geomagnetic field. This angle β is a function of the geographical latitude Λ, the magnetic inclination I, the local time Φ, and the solar declination δ according to the expression

$$\cos \beta = -\sin \delta \cos (I + \Lambda) + \cos \delta \sin (I + \Lambda) \cos \Phi$$

In Figure 1 the function $g(\alpha)$ is plotted as a

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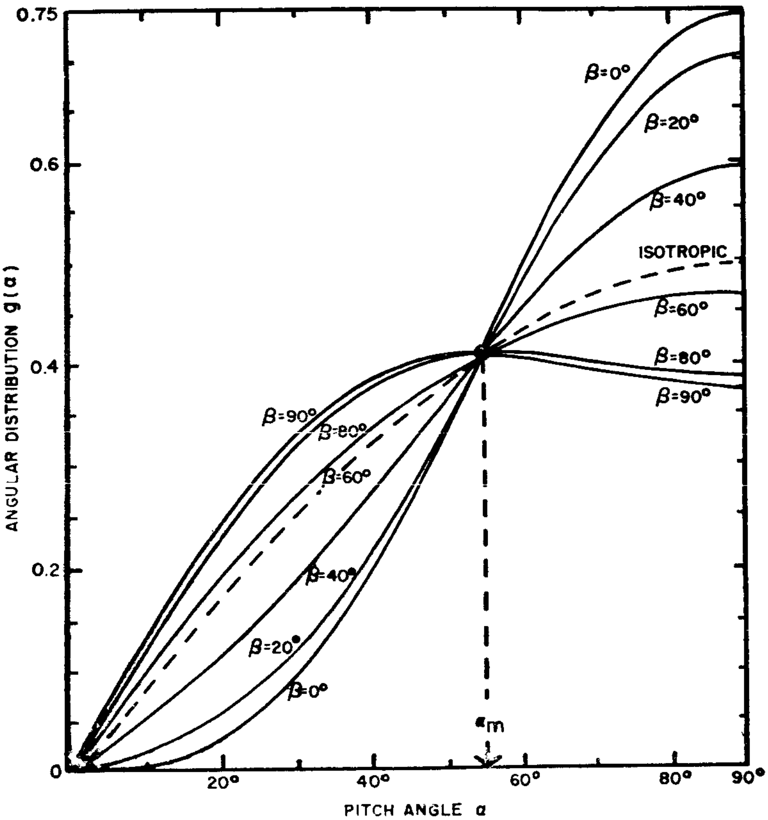

Fig. 1. Pitch-angle distribution of the photoelectrons for different values of the angle β. The dotted line gives the distribution in the case of an isotropic angular distribution. The angle α_m is the abscissa of a point common to all curves.

function of pitch angle for different values of β. The photoelectrons with rather small pitch angles can drift along the magnetic line of force within a narrow cylinder whose radius has an upper limit of some tens of centimeters. The photoelectrons with high pitch angles, instead, cannot migrate significantly. The fraction of photoelectrons with intermediate pitch angles α actually able to drift along the magnetic lines of force increases sharply when β increases.

Figure 2 shows the percentage of photoelectrons cm^{-3} sec^{-1} having pitch angles between 0 and a maximum angle $\alpha_m = 54.6°$ for different times at the equinoxes and the solstices. We consider now what happens at low latitudes. The less energetic of the upgoing photoelectrons are gradually stopped along their spiral path toward the equatorial plane, and only the more energetic ones can possibly reach the conjugate point. The photoelectrons going down are instead lost in the lower ionosphere where stopping processes other than elastic collisions with ambient electrons play a predominant role. Thus, their relative contribution to the existing photoelectron production rate is obviously small; this is not the case of the upgoing photoelectrons at heights where the local production is very small.

Our problem is to estimate the 'actual' production at a given place A_i (Figure 3). In the semiqualitative approach given in this letter, we assume:

1. All photoelectrons produced below the 300-km level cannot escape, independent of their energy.
2. The photoelectrons produced above 300 km can escape according to the pitch-angle distribution $g(\alpha)$ only if $\alpha \leq \alpha_m = 54.6°$.
3. The escaping photoelectrons lose their energy in elastic collisions with ambient electrons

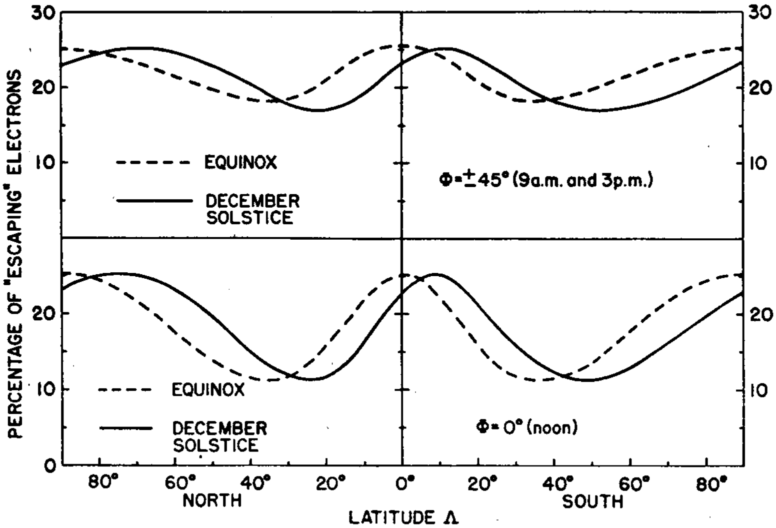

Fig. 2. Percentage of 'escaping' photoelectrons cm^{-3} sec^{-1} (electrons with pitch angle less than α_m) as a function of latitude at different times and seasons. The local time is expressed by the hour angle Φ ($\Phi = 0°$ at noon).

without undergoing, on the average, appreciable variation of their pitch angle α.

We remark that, at least at low latitudes, the height profile of the photoproduction rate above the 300-km level at noon is almost insensitive to latitude variations, so that we can make the further hypothesis:

4. The production rate between 40°N and 40°S above 300 km is a known function of the height h only.

At the points A_1, A_2, A_3, etc., at a constant height h above the ground, the fraction of photoelectrons able to escape upward or downward along the magnetic lines of force is steadily decreasing from 0° to 35° at the equinoxes. As a consequence of this photoelectron drift, the 'actual' production is appreciably greater at tropical latitudes than at the equator.

On the other hand we must also take into account the fact that, because of the very small ambient electron density at heights above 1000 km, a certain latitude-increasing part of the escaping photoelectrons can possibly penetrate, more or less deeply according to their energy, the upper ionosphere into the opposite hemisphere. This effect can balance part of the 'magnetic depletion' effect at latitudes above about 20°.

In practice, the largest absolute contribution to the escaping photoelectrons is confined to the height interval between 300 and 500 km. The total number of escaping photoelectrons has been estimated [*Hanson*, 1963] to be of the order of 10^8 cm^{-2} sec^{-1}. If they were uniformly lost along a line of force, they could give an average supplementary 'production' density of 10^8/(average length of magnetic line), whose upper limit cannot be more than 1 electron cm^{-3} sec^{-1}. Such a production is possibly important only in the equatorial region where it is distributed at higher levels than at other latitudes. The net effect could give some contribution to the experimentally observed higher altitude of maximum electron density at the equator, despite the lower altitude of the maximum of the photoelectron production.

The magnetic depletion effect increases again at latitudes above approximately 35°. If we take into consideration the latitudinal variation of the atmospheric structure, which we completely neglected here, and the minor effect between conjugate points, it seems reasonable to expect some maximum of ionospheric electron density at some intermediate latitude, possibly just in the tropical region. On the other hand, we must expect some appreciable longitudinal dependence of the magnetic depletion effect due to actual inclination of the magnetic dipole axis with respect to the geographic axis.

Concerning the contribution of the magnetic

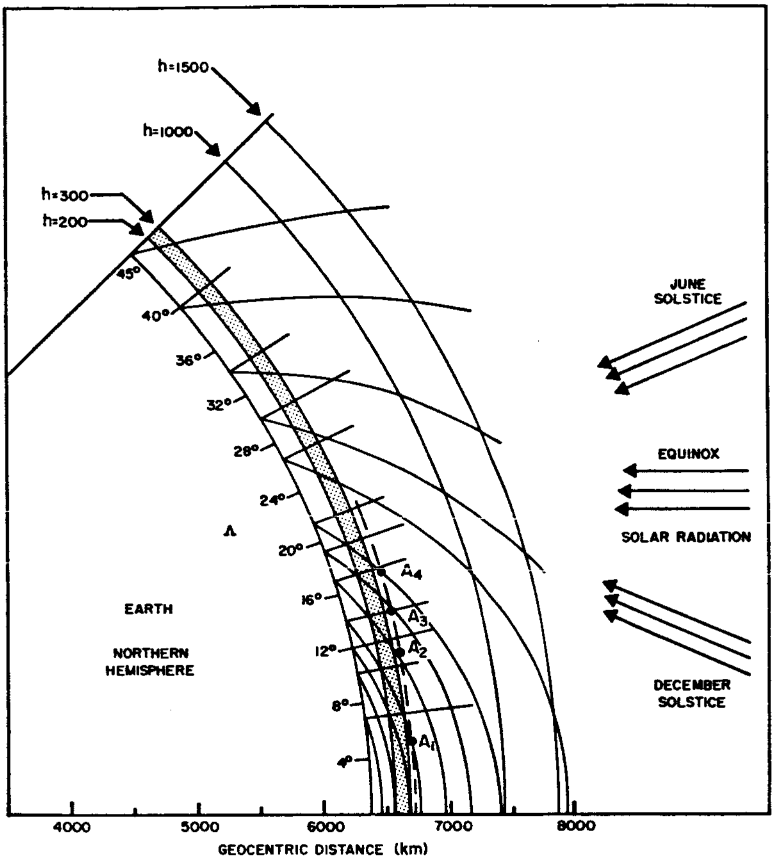

Fig. 3. A representation of the geomagnetic lines of force. Different constant geometrical height lines are also shown. The dotted region indicates the height interval in the F_2 layer within which all the energetic photoelectrons are 'locally' lost. The direction of solar incoming radiation at equinoxes and solstices is indicated.

depletion at other times than noon, we see (Figure 2) that the effect is maximum just at noon; no differential latitude depletion occurs at the equinoxes at 6 AM (or 6 PM), because the angle β is zero. However, the geomagnetic anomaly in the later afternoon or after sunset is obviously an effect of the hysteresis (or, in other words, of the long lifetime) of the F_2 layer.

The situation in solstice months, for example in December, may be as follows: We see, from Figure 2, that in this case the magnetic depletion effect is a maximum at 10° latitude south and the minimum depletion occurs when $\Lambda \simeq 25°$ in the northern (or winter) hemisphere and $\Lambda \simeq 50°$ in the southern (or summer) hemisphere. There must be, in other words, some southward shift of the equatorial minimum of the photoelectron production. This is just what appears to be the case, according to the analysis by *Thomas* [1963].

Moreover, within the limitations given by hypothesis 4, we can also expect a higher electron production in the winter hemisphere at low latitudes. This could result in an important contribution to the winter anomaly in this latitude range.

At higher latitudes the percentage magnetic depletion effect is greater in the winter hemisphere than in the summer one. This is just in the opposite sense to contribute to the winter anomaly. However, no definite conclusion can be drawn in this latitude range without taking into proper account the latitudinal variation of the atmospheric structure which is certainly much more effective at solstices than at equinoxes in giving latitudinal variations and differences between northern and summer hemispheres.

A more quantitative approach to the problem encounters difficulties because we must know, at least approximately, the energy spectrum of the photoelectrons and the true-height profile of ambient electrons over a rather extended range of latitudes and times. Work along these lines is now in progress.

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